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A Study on Probabilistic Slope Stability Analysis for Different Slope Geometries and Variation Levels

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Abstract. Soil is naturally occurring material, so considering spatial variability residing in soil properties seems logical. Assessment of Probability of Failure (PF) adds a more aspect in determination of safety of a system. In this study, probabilistic analysis along with deterministic analysis is carried out for different slope angles and variation levels of shear strength properties. Deterministic factor of safety, probabilistic factor of safety and probability of failure is calculated for different slope geometries with and without consideration of cross-correlation between cohesion and friction angle under static condition. Effect of different variation levels on slope under dynamic condition is also studied. Three different LEMs have been utilized for analysis and random variables are considered to follow normal distribution. The results prove that FOS and PF have an inverse relationship which is non-linear but their non-linearity is greatly affected by COV levels. Results prove that the critical slip surface with minimum FOS obtained through deterministic analysis may not be the critical slip surface after all. Probability of failure (PF) more than 10% is not acceptable in any case. Probabilistic analysis along with deterministic analysis should be carried out to fully consider the geotechnical risk and hazard.

Keywords: Uncertainty, Probabilistic Analysis, Spatial Variability, Probability of Failure, Coefficient of Variation.

1 Introduction

Hazard assessment of dykes, embankments, landfills, open pit mines, earthen and rockfill dams, tailing dams, natural and man-made slopes, etc. are important for effective function of the system and mitigate the system for any possible natural hazard. In geotechnical engineering, for the most of assessment purpose, concerned soil in use and in foundation is assumed to be homogeneous and the property values are believed to be true representation of natural soil. Actually, this condition is very hypothetical because to have the truest representation of soil, the error in sampling and testing should be NIL. This is seldom a case, especially in those countries where there are not strict regulations about true representation of soil. In most of the sampling techniques, samples are obtained by thorough application of dynamic forces and larger equipment. Maintaining a higher degree of quality while working with large equipment and dynamic forces is not possible. In the analysis methods also, to make analysis simpler, so many assumptions are adopted. In addition, there always is an inherent variability residing in the soil. Variability in soil property may also due to a smaller number of bore holes excavated in the soil exploration and the rest of the data evaluated by either interpolation or extrapolation. Unlike variability of manufactured parts in structural and mechanical engineering under perfectly controlled conditions, variability in geotechnical field is way more complex and may be due to disparate sources.

The three primary sources of geotechnical uncertainty are *inherent soil variability*, *measurement and miscalculation error* and *transformation uncertainty*. The degree of uncertainty arising from above mentioned sources depends on soil profile at the site, the quality control maintained at the site and laboratory while sampling and actual procedure of testing, and the precision level of transformation tool or model utilized for transformation of test results into the required soil property [1]. Baecher and Christian classified geotechnical uncertainty as *Natural Variability*, *Knowledge Uncertainty* and *Decision Uncertainty*. Natural uncertainty resembles to inherent soil variability and has two aspects as temporal variability and spatial variability. Temporal variability is variation at a same place happening over a course of time. While spatial variability is variation in properties at different places on a particular time. Knowledge uncertainty is due to lack of knowledge about the characteristics of soil, process of testing and data interpretation. Decisional uncertainties deal with inability to know social objectives, length of planning of project, desirable temporal consumptions, social aversion to risk, etc. [2]. Conventional slope stability analysis considers uncertainty implicitly. Analysis methods already have numerous assumptions and they result into a single value of FOS. Due to ignorance of such uncertainties, obtained FOS is not much reliable and mislead the concept of safety hence compromising the adequacy of the safety of system. Probabilistic analysis is a powerful method to incorporate uncertainties and is very easy to applicable on practical problems without extensive efforts which needed in conventional limit equilibrium methods [3]. Coefficient of variation (COV) is the most useful parameter to take into consideration the uncertainty residing in soil. COV is the ratio of standard deviation to the mean value and is generally represented as a percentage. Different COV percentages represent different variation levels. COV percentages less than 10% is generally considered as lower variability, that of more than 30% is considered as higher variability, and COV between 10% to 30% is moderate variability [4]. Logically, FOS and PF should have inverse relationship, meaning that higher safety factor indicates less risk of failure and vice-versa. COV has a significant effect on FOS-PF relation and their characteristic non-linear relation is greatly affected by different COV levels [4]–[6]. In probabilistic analysis, it is assumed that the various values of spatially variable parameters follow a specific type of distribution (i.e., normal, beta, gamma, exponential, logarithmic, uniform, triangular, etc.). In order to know distribution of spatially variable parameter, thorough investigation and sampling at different places and depths needs to be carried out and tested for the desired geotechnical property. Shear strength parameters cohesion and angle of internal friction, bulk unit weight (γ_b), moist unit weight (γ_t), dry unit weight (γ_d), and water content (w) follow normal distribution [7]. Normally, for the geotechnical parameters, normal distribution is only used.

Comparative studies carried out for use of different distributions showed that beta distribution gives higher PF for the same case than that of given by normal and lognormal distributions. So, they suggest to adopt beta distribution for various parameters [8]. Depending on these distributions, the program generates specified numbers of random samples and then assign those sampled values to model and carries out limit equilibrium analysis. Now these random samples to be more logical, specification of cross-correlation between concerned parameter is necessary. Suppose, in the samples, if cohesion (C) values are increasing then the values of friction angle (φ) should be decreasing to make analysis seem truer and logical. To incorporate this matter, cross-correlation has to be defined between cohesion and friction angle. Cross-correlation does not only exist between cohesion and friction angle, but also between cohesion and unit weight, friction angle and unit weight, unit weight and water content and etc. Cross-correlation value between C and φ ranges from -0.37 to -0.7 [9]. On the other hand, unlike negative cross-correlation between C and φ, correlation values between C and γ and φ and γ are positive and in the range of 0.5 to 0.9. And as expected, there is no correlation between C and γ_d [7].

In this study, probabilistic slope stability analysis along with deterministic analysis is carried out by using three different limit equilibrium methods as Bishop's Simplified Method, Spencer's method and Morgenstern-Price's Method. The effect of different COV levels of random variables as shear strength parameters (Cohesion and Angle of Internal Friction) on different slope geometries is investigated under both static condition and dynamic condition. Influence of different COV levels on FOS-PF relationship is also studied. The effect of cross-correlation between shear strength parameters of soil is also investigated. The results obtained through three LEMs are analysed for evaluation of percentage error between results of three LEMs.

2 Materials & Methods

Deterministic and probabilistic slope stability analysis is carried out using a commercially available software named Rocscience SLIDE. It is a 2-D Limit Equilibrium Analysis tool for the assessment of slope stability.

2.1 Slope Geometry:

In this analysis, slope height of 23 m and slope length of 75 m is considered. Investigation for different slope angles ranging from 25 degree to 46 degree is carried out. Different slope angles considered are 25°, 32°, 34°, 36°, 38°, 40°, 43°, & 46° in static analysis while for analysis with cross-correlation, slope angles of 25°, 36°, 40°, 46°. Dynamic analysis is carried out for slope angles of 32°, 36°, 40°, & 46°.

2.2 Materials:

In this study, deterministic and probabilistic analysis of a soil slope model prepared in software is carried out. The material properties for slope and foundation are taken from a site in Karamsad, Anand, Gujarat, India. A thorough soil exploration is carried out for 30 meters of depth. Entire soil exploration consists of two bore holes with 30 m depth each. The soil in foundation, majorly consists of clay with different plasticity, silty clay and sandy silty clay. In this study, foundation depth of 12 is considered because beyond 12 m a fairly firm strata with SPT value of 66 is present. The material which is used in slope, its properties are also obtained from the same site. Properties of material used in slope and foundation material is displayed below:

Table 1. Soil Properties Adopted for Slope (Mean Values)

Sr.No.	Soil Property	Value
1	Cohesion (C)	0.1 kg/cm^2 (9.8 kPa)
2	Angle of Internal Friction (φ)	25°
3	Unit Weight (γ)	1.5685 gm/cc (15.382 kN/m^3)

Table 2. Material Properties for Foundation

Foundation Depth	Material Property	Value
8.5 m	Cohesion (C)	0.1 kg/cm^2 (9.81 kPa)
	Angle of Internal Friction (φ)	24°
	Unit Weight (γ)	1.5685 gm/cc (15.382 kN/m^3)
3.5 m	Cohesion (C)	0.89 kg/cm^2 (87.28 kPa)
	Angle of Internal Friction (φ)	12°
	Unit Weight (γ)	1.623 gm/cc (15.92 kN/m^3)

The random variability is considered to be present only in the slope material. Coefficient of variation (COV) is the most useful parameter in order to include the residing uncertainties in the soil. COV is defined as ratio of standard deviation to the mean values and is generally represented as percentage. COV is the measure of deviation of the parametric value with respect to the actual (mean) value. COV is the most commonly used parameter in the statistics to evaluate the percentage deviation of the value from the mean value. In this study also different COV levels of random variables are chosen and they are assumed to vary in the range of 5% to 40%. Generally, COV of shear strength parameters used to vary from 5% to 50% which has been used and proven by many of the researchers [4], [5], [7], [10], [11], [12]. Cohesion (C) and angle of internal friction (φ) are considered as random variables. Different COV % values for cohesion and friction angle are assumed as 5%, 13.75%, 22.5%, 31.25%, & 40%. Cross-correlation always exists between different parameters of soil such as cohesion, angle of internal friction, unit weight, pore pressure parameters, water content, etc. These values of cross-correlation may either be positive or negative. In this study, cross-correlation between cohesion and friction angle is considered only. Cross-correlation between C and φ generally have inverse relationship [7], [9]. Therefore, negative value of correlation has been used for shear strength parameters of soil in probabilistic analysis. This value of cross-correlation has been reported to vary between -0.37 to -0.7 [9]. Normally, the most used value of cross-correlation is -0.5 to -0.7 and have been used by numerous researchers as well [4]–[6], [13].

Table 3. Statistical Properties used in this study

COV %	Cohesion (C)		Angle of Internal Friction (φ)	
	Mean Value	Standard Deviation	Mean Value	Standard Deviation
5	9.8	0.49	25	1.25
13.75	9.8	1.3475	25	3.4375
22.5	9.8	2.205	25	5.625
31.25	9.8	3.0625	25	7.8125
40	9.8	3.92	25	10

2.3 Method:

SLIDE 2-D limit equilibrium analysis tool has been used in this study to carryout deterministic and probabilistic slope stability analysis. Limit equilibrium method is a very popular and widely used method for assessing the stability of slope. Out of all the methods available in software, in this study, Simplified Bishop's Method, Spencer's Method and Morgenstern-Price's Method have been used. The reason behind using three method is to check legitimacy of the data and to evaluate the percentage difference between the data obtained through these methods. In probabilistic analysis, depending on the specified number of samples, the samples are randomly generated for variable parameters (cohesion and friction angle in this case) and then those parametric values are assigned to prepared soil slope. After assignment of values to the randomly variable parameters, firstly deterministic analysis is carried out for specified LEMs and then for the critical slip surface with minimum FOS, probabilistic analysis is carried out with different values of variable parameter over the same slip surface. The different values of the parameter in the probabilistic analysis are the same values generated during the random sampling. The result of probabilistic analysis is displayed in terms of probabilistic FOS, probability of failure (PF) and reliability index (β). Probability of failure is defined as number of slip surfaces with FOS less than 1 to the total number of surfaces analyzed.

The software provides two types of probabilistic analysis: Global Minimum (GM) type analysis and Overall Slope (OS) type analysis. Although the results of both the types of analyses are almost same but the difference between these two methods lies in the way they perform analysis and the run time. In this study, only GM type analysis method is adopted.

For random sampling, either Monte-Carlo sampling (MCS) technique or Latin Hypercube sampling (LHS) technique can be used. Both the methods are unbiased estimation techniques but the only difference is the level of accuracy achieved in both the methods for given number of samples N. If one wants to have a desired accuracy for N number of samples by using LHS, then to achieve the same desired level of accuracy by MCS, N^2 number of samples will be required. In this study, MCS technique has been utilized for sampling. Although LHS is more reliable accurate, MCS method is more popular and widely used [3], [4], [6], [10], [14], [15].

The number of samples chosen is also important. The samples should not be too less that the value of concerned parameter does not converge to a single value. To check this, graph of concerned parameter v/s number of samples chosen is plotted. Before the graph reach to final number of samples, the graph should be the least varying and converging towards a single value of parameter. In this study, 1500 numbers of samples are chosen. The number is decided through preliminary simulation carried out before actual simulations. There is no any ideal number for sampling which can be used for any case. Number of samples differ by case to case and totally dependent on the conditions considered, type of analysis and level of accuracy required. In this study, failure direction is set to occur from left to right. Random sample generation technique is set to be Pseudo-Random method rather than fully random method

Effect of dynamic forces over the different slope angles and different variation levels is also considered. The concerned site is located in seismically active zone III and accordingly the peak ground acceleration (PGA) values for this site is obtained from Indian standard design code as IS: 1893: Part 1 (2002) [16]. The code suggests to use the values of PGA or zone factor in zone III as 0.16 at ground level in horizontal direction. These values should be reduced to half for foundation depth of 30 m and in between varying linearly. The summary of PGA value used is shown below:

Table 4. PGA values for in Horizontal and Vertical Direction for Zone III (IS:1893Part-I)

Zone Factor for Seismically Active Zone III	0.16
PGA for Horizontal Direction (12m depth)	0.128 (0.8 * 0.16)
PGA for Vertical Direction	0.064 (0.5 * 0.128)

3 Results & Discussion

Considering all the types of combinations of different COV% levels of shear strength parameters, different LEMs, under static condition, condition with correlation, & under dynamic condition, a total of 400 numbers of slopes have been analyzed. With use of three different LEMs and evaluation of three parameters as deterministic FOS, probabilistic FOS and probability of failure, total 3600 numbers of data have been obtained through simulations. These data have been analyzed by using Microsoft Office Excel 2019. The result of simulation is presented below.

The first set of analysis is carried out for eight different slope angles as 25°, 32°, 34°, 36°, 38°, 40°, 43°, & 46° in static condition without consideration of cross-correlation between shear strength parameters. Relation between COV% and PF is non-linear (Figure. 1). For a given slope angle increment in COV% affects differently on PF-COV% relation depending on the deterministic safety level (i.e., FOS > 1 or < 1). Slopes with angle less than 40°, are deterministically safe having FOS > 1 and those of with angle more than and equal to 40°, are deterministically unsafe having FOS < 1. Results indicate that for safer slopes, increment in COV% increases PF. While the unsafe slopes, increment in COV% decreases PF for a particular slope angle. Similar results also have been reported by some researchers [4], [17], where they showed that increment in COV%, increases PF for slopes with FOS > 1 and PF decrease for slopes with FOS<1.

As can be seen from Figure. 1, for comparatively safer slope angles (from 25 to 38 degree), as variation level (COV%) increases, PF also increases. While this trend seems to be reversed when slope becomes deterministically unsafe. As slope angle increases and lead towards the failure limit, the PF for same level of COV also increases. For 0% of COV the probabilistic and deterministic analysis are same and in deterministic there are no chances of whether the failure will occur or not; failure either will occur or will not occur. Since, slopes with angle less than 40 degree are safe, their PF is 0 and that of for slope angles more than and equal to 40 degree 100%. For lower slope angles, the change in PF is lower and gradual and as slope angle increases, initially the change in PF is sudden and becomes gradual later on. For example, for 25-degree slope, as COV% increases, change in PF is less and increases gradually; while for 38-degree slope, change in PF is drastic when COV% increased from 0 to 5% and then the increment in

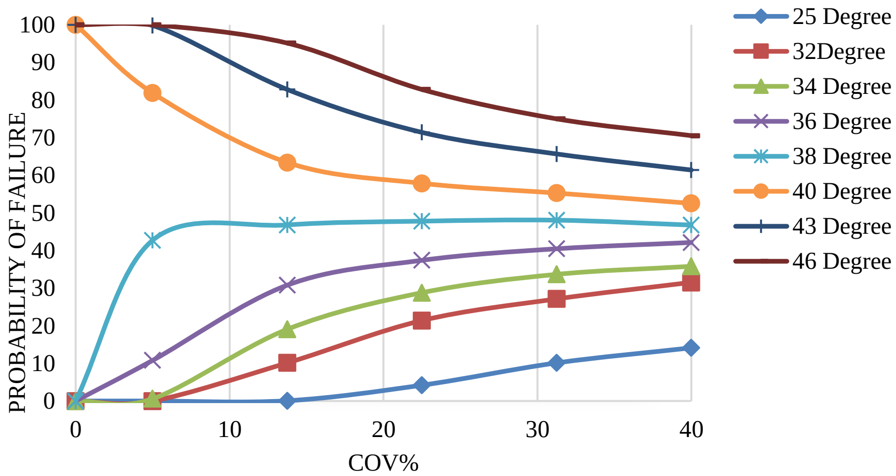


Fig. 1. PF v/s COV% Relation for different Slope Angle

gradual. On the other hand, comparatively unsafe slopes (slope angle ≥ 40-degree), increment in COV% reduces PF and for same level of variation, increased slope angle increases PF.

For the same analysis set, Figure. 2 displays the relationship of FOS and PF and how does COV% affects their behaviour. The highlighted points on each curve represents a specific value for specific slope angle. Slope angles are varying from 25-degree to 46-degree, as we move from left to right. It can be interpreted from the graph of FOS v/s PF that the relation between then is non-liner and their relation is very much dependent on COV levels.

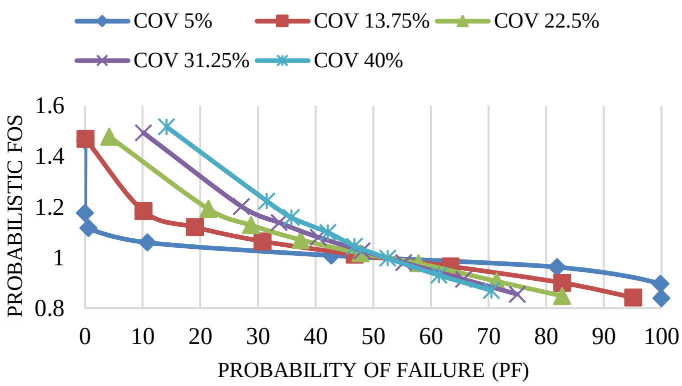


Figure 2 Effect of Different COV% levels on FOS-PF Relation

For lower COV levels (such as 5%), the relation between FOS and PF is highly non-linear and kind of like deterministic analysis i.e., when FOS > 1 then PF < 50% (nearer to 0-30%), but when FOS < 1 then PF > 50% (nearer to 70-100%). Alternatively, when COV is 0%, the analysis becomes deterministic analysis and there isn't any need to carry out probabilistic analysis anymore because even after conducting probabilistic analysis, results will be the same as deterministic analysis. The graph also shows that as the COV level increases from 5% to 40%, the FOS-PF relation tend to become linear. Also, this indicates that, as COV level increases, PF tend to increase as well. Deterministically safe slopes with FOS values as 1.099 and 1.223 for COV level of 40% has probability of failure as 42.133% and 31.533% respectively. But at lower level of COV as 5%, deterministically safe slopes with FOS 1.059 and 1.176 has probability of failure as 10.8% and 0% respectively. This proves that, for larger values of COV i.e., significant variation in variable properties, results in higher values of PF even for deterministically safe slopes. Hence, only deterministic analysis is not sufficient enough to fully analyse the slope and along with-it probabilistic analysis should also be carried out in order ensure the safety of the slope.

The next set of analysis is carried out for different slope angles with consideration of cross-correlation between shear strength parameters. The behaviour of different soil parameters is intertwined with the behaviour of other parameters. This intertwined behaviour of parameters is generally represented by correlation factor. Correlation factor between two parameters describe the behavioural change in one parameter if value of another parameter is changed. In this study, cross-correlation between cohesion and angle of internal friction is considered. This correlation is mostly negative in nature and may range between -0.37 to -0.70 [9]. In this study, cross-correlation between C and φ is assumed to be -0.5. A series of slope analysis is conducted for different slope angles as 25°, 36°, 40° & 46° and the results are compared with the slope models without consideration of cross-correlation. The following Figure. 3 displays comparison for the slope angle 25 degree with and without correlation for cohesion and angle of internal friction. The deterministic and probabilistic FOS for slope angle 25 degree varies between 1.4 to 1.5. Consideration of cross-correlation slightly decreases the PF than without consideration of cross-correlation. Since, FOS is more than 1, PF has a range 0 to 15% (closer to 0). This characteristic is similar to all the slopes with angle less that 40-

degree i.e., deterministically safe slopes. Figure. 4 displays the effect of various levels of variation over FOS-PF behaviour. With increment in COV values, PF decreases. The results seem to be same for all the slopes with FOS < 1. For this slope, deterministic and probabilistic FOS ranges from 0.83 to 0.87 and PF ranges from 70% to 100%. For this slope, consideration of cross-correlation slightly increases the probability of failure.

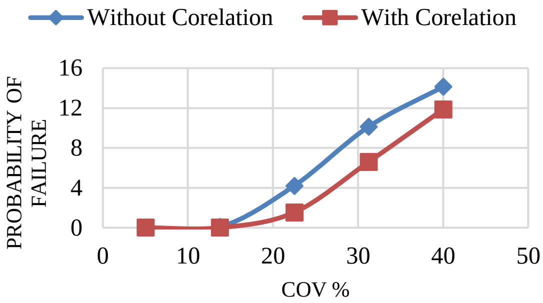


Figure 3 Effect of Cross-correlation on PF-COV Relation (25 Degree Slope)

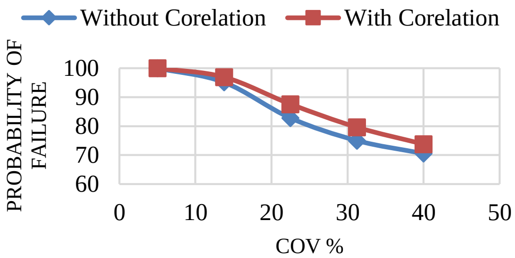
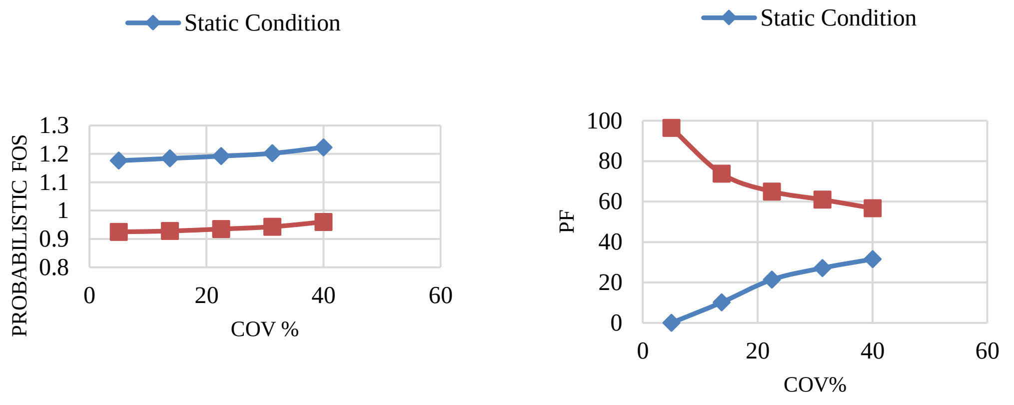


Figure 4 Effect of Cross-correlation on PF-COV Relation (46 Degree Slope)

The final set of analysis is carried out with inclusion of dynamic forces. Karamsad, Anand is located in seismically active zone III.. Slope angles considered for dynamic analysis are 32°, 36°, 40°, & 46°. The effect of dynamic forces over the relation of FOS-PF and PF-COV% is displayed in following figures. Figure. 5 shows the results for slope angle 25-degrees. As can be observed from the Figure. 5-(a) that, consideration of dynamic loading significantly reduces the FOS. This can be due to reason that, extensive shaking caused by earthquake increases the spatial variability of material properties. And as proven in previous sections that, as variation level increases, probability of failure also increases. Means that higher variability reduces the FOS and hence making the slope prone to failure. This point is also gets proved by Figure. 5-(b). It can be seen from the graph that; consideration of dynamic parameter leads to significant increment in PF. The soil slope models developed in SLIDE software for the analyses of slopes of angle 32 degree and 46 degree are shown in figures 8 and figure 9 respectively.



(a) (b)

Figure 5 Effect Due to Dynamic Forces (32-Degree Slope) (a) Plot of FOS v/s COV%, (b) Plot of PF v/s COV%

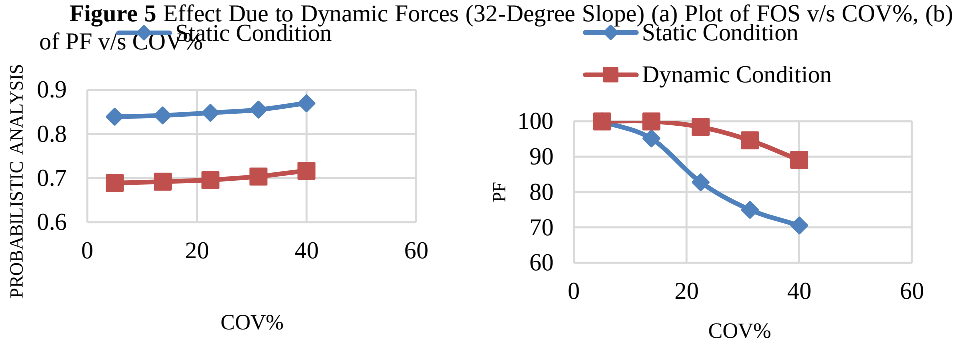


Figure 6 Effect Due to Dynamic Forces (46-Degree Slope) (a) Plot of FOS v/s COV%, (b) Plot of PF v/s COV%

Figure. 6 displays the results of analysis conducted under dynamic condition for slope angle 46-degree. Figure. 6 shows that probabilistic FOS which was already lower than 1 having range of 0.8 to 0.9 lowers down to a range of 0.68 to 0.72, proving that earthquake forces cause more disturbance and makes slope prone to failure under earthquake conditions. Figure. 6 also reflects the same results and confirming that earthquake forces increase PF than the static condition.

Figure. 7 displays results for slopes different angles studied with different COV values under dynamic conditions. Each point on the curve represents a result for specific slope angle from 32, 36, 40 and 46 degrees. As can be observed from the graph, for same slope angle as COV% increases, FOS increases as well and simultaneously PF decreases which is logical. At smaller variations, relation of FOS-PF is non-linear and as COV% increases, the graph becomes more of a linear kind. This behaviour under dynamic condition is same as followed under static condition (Figure. 2).

4. Conclusions

In this study, probabilistic slope stability has been carried out. The effects of various variation levels, consideration of cross-correlation between cohesion and angle of internal friction, static and dynamic forces over the probabilistic analysis is investigated. A total of 400 numbers of slope have been analyzed, which have evaluated 3600 numbers of data.

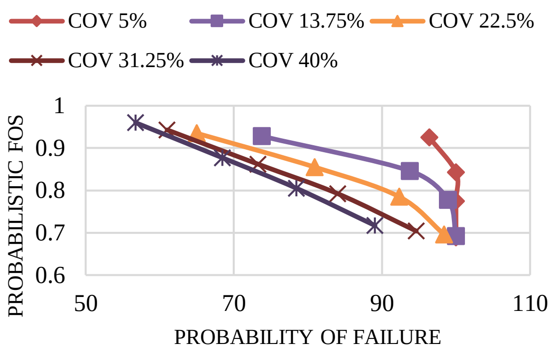


Figure 7 The Non-linear Relation between FOS & PF and the effect of COV% under Dynamic Condition

Figure 8 *Model Developed in Software for 32-degree Slope*

Figure 9 *Model Developed in Software for 46-degree Slope*

- Slopes with angle less than 40° are relatively safe, having FOS > 1 and PF < 50% for different values of COV% and slopes with angles more than 40° are unsafe, having FOS < 1 and PF > 60% (mostly near to 100%).
- For the slopes with angle less than 40 degree, as COV% of Cohesion and COV% of Angle of Internal Friction increases, Probability of Failure increase. Meaning that higher spatial variability leads to more disturbance in the slope and hence increased PF. On the other hand, slopes with angle 40 degree and more, as COV% of Cohesion and COV% of Angle of Internal Friction increases, Probability of failure reduces.
- The relation between FOS v/s PF is very much non-linear and their non- linearity is significantly affected by COV% levels.

- The correlation between C and φ is assumed to be -0.5. For safer slopes consideration of cross-correlation slightly reduces the PF. Although, the trend followed by case with correlation and without correlation seem to follow same trend, i.e., as COV% increases, PF also increases. On the other hand, for unsafe slopes, consideration of cross-correlation slightly increases the PF. In this case also, the curve for both cases with correlation and without correlation follows the same pattern i.e., increment in COV% causes reduction in PF.
- Errors between the results obtained through different LEMs, are not more than 1% and error in PFs vary between 1 to 2% and few cases up to 10%.

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